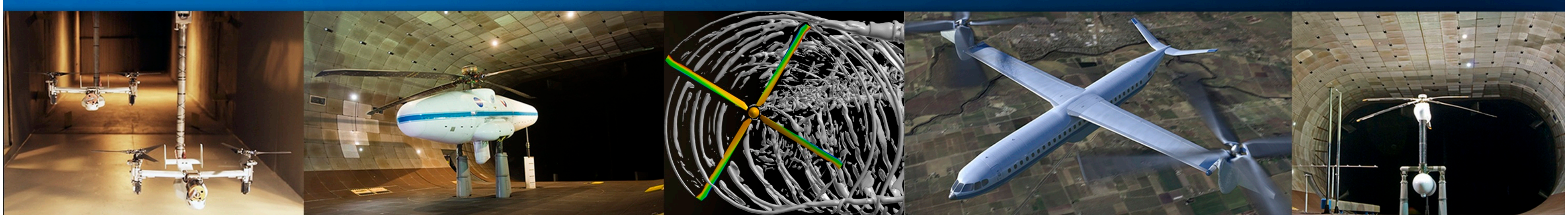
National Aeronautics and Space Administration

High Advance Ratio Testing Experiences

Tom Norman

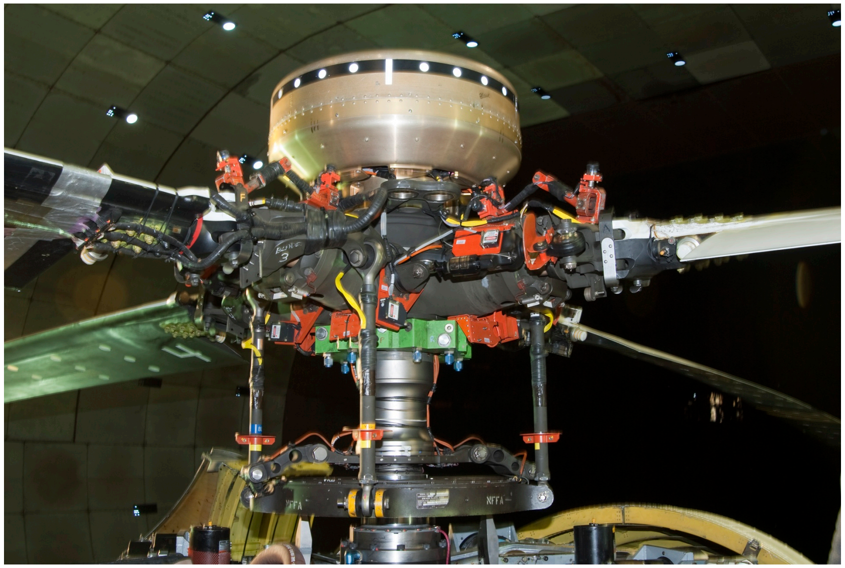
NASA Ames

STAR Meeting – April 30, 2012



Background

- UH-60A Airloads wind tunnel test conducted in USAF National Full-Scale Aerodynamic Complex (NFAC) 40- by 80-Foot Wind Tunnel (2010)
- One objective was to evaluate production rotor at slowed-rotor conditions

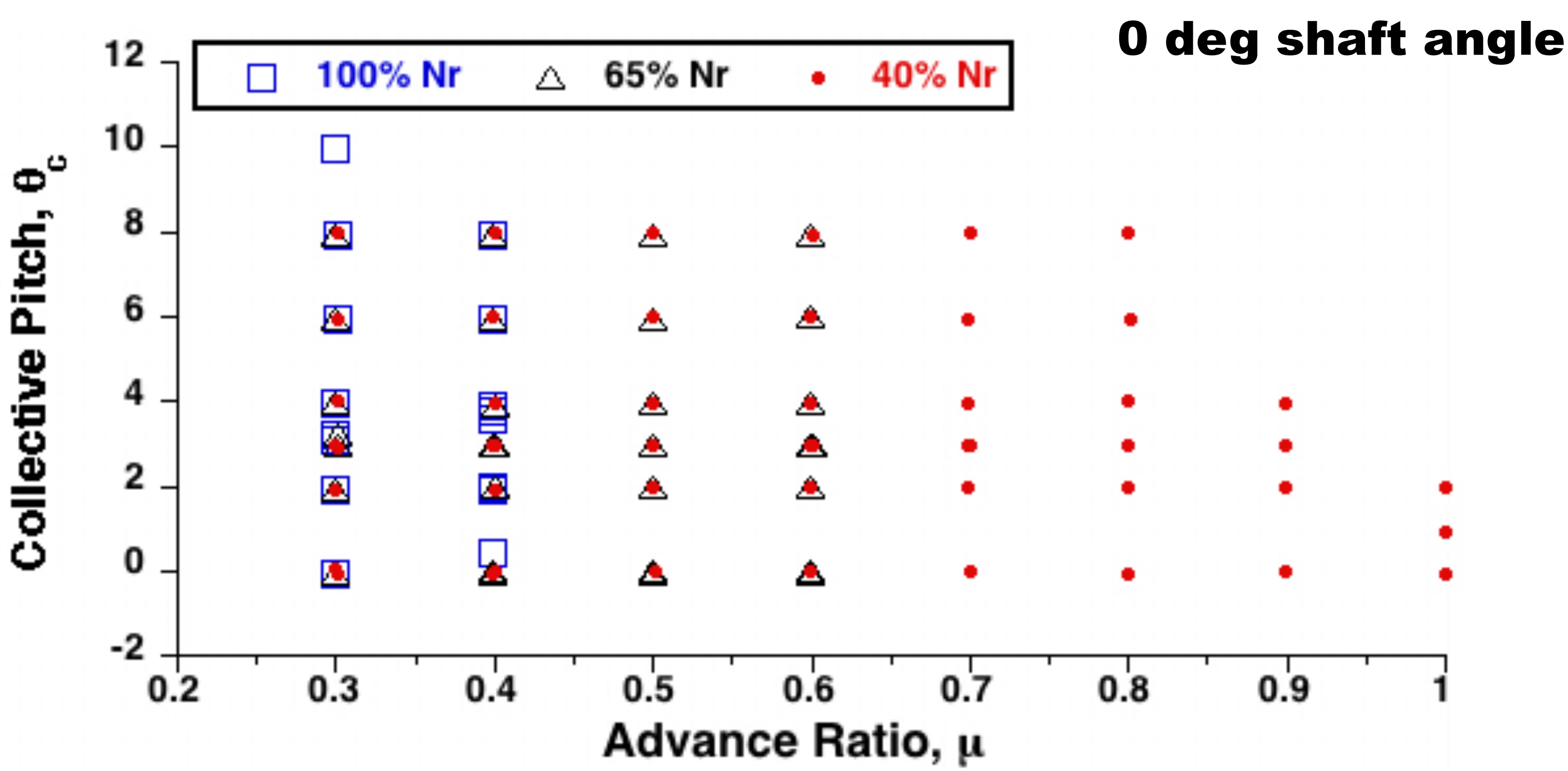


UH-60A Slowed Rotor Testing

- Objective
  - Acquire unique aerodynamic and loads data for non-conventional operating envelopes representative of slowed-rotor configurations
- Approach
  - Acquire data up to advance ratios of 1.0 by reducing rotor RPM as low as 40% nominal
  - Perform parametric sweeps of collective, shaft angle, and advance ratio at 3 different RPM's (100%, 65%, 40%)

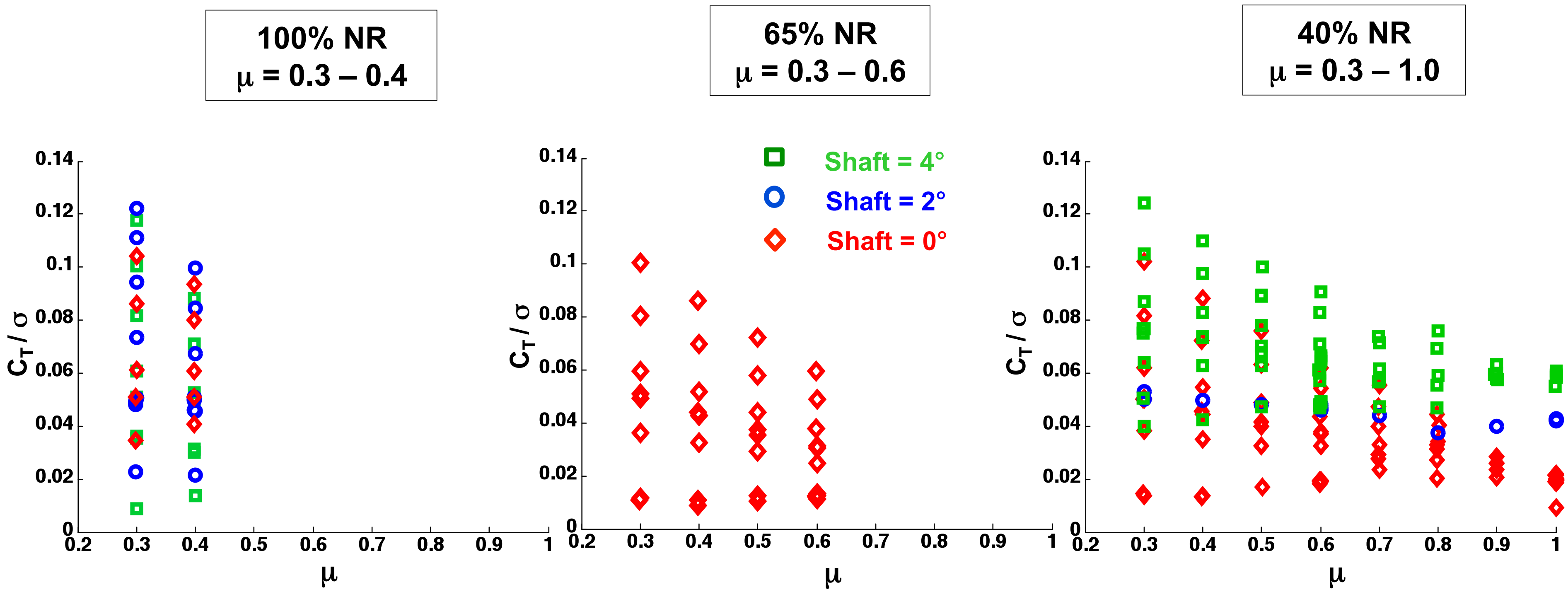
Slowed Rotor Test Data Acquired

- Slowed Rotor Testing
  - Collective sweeps at 3 hover tip Mach numbers and 3 shaft angles up to advance ratios as high as 1.0



Thrust (C_T / σ) vs. Advance Ratio (μ)

100%, 65%, and 40% NR



- **Detailed analysis of resultant performance, airloads, and structural data in Datta et al (2011)**

Outline

- Pre-test Analysis
  - Analysis for “standard” operations
    - Structural limits
    - Rotor loads and motion
    - Dynamic stability and ground resonance
    - Operational issues
  - Analysis for “emergency” operations
    - Tunnel and drive system failures
  - Resultant test procedures, SOF monitoring requirements, and test envelope
- Testing Experience

Analysis for “Standard” Operation

- Structural SOF limits
  - Evaluate validity of existing SOF limits
    - Lower RPM reduces CF – may change load limits
    - Lower RPM may change SOF area – i.e. trailing edge strength
    - Ensure (or add) gages available for safety monitoring

Analysis for “Standard” Operation

- Rotor Loads and Motion
  - Perform analysis to estimate rotor loads and control motions to identify clear problem areas
  - High advance ratios have unique control characteristics
    - Thrust vs collective reverses at high mu
    - Long cyclic (or flapping) increases as advance ratio, collective, and/or shaft angle increase
    - Lat cyclic (or flapping) increases as advance ratio increases
  - Rotor motions likely to limit test envelope
    - Ensure clear limits on pitch, flap, and lag

Analysis for “Standard” Operation

- Dynamic Stability and Ground Resonance
  - Perform analysis to estimate dynamic stability at lower RPM
    - Consider stability testing during operations to ensure stable rotor
    - At the minimum, monitor key parameters to look for unexpected behavior
  - Review ground resonance analysis at reduced RPM
    - Avoid RPM’s close to predicted modes
    - Evaluate lag dampers at reduced frequency to ensure damping characteristics understood
    - Consider stability testing during operations to ensure stable rotor
    - At the minimum, monitor key parameters to look for unexpected behavior (damper motion, balance channels)

Analysis for “Standard” Operation

- Operational Issues
  - Even with analysis, still need to be very careful
  - Monitor SOF channels and evaluate stability as you go
  - Change only one thing at a time – make sure that you can go back to original condition safely (no ground resonance crossings)

- Unique high advance ratio characteristics drove plan for operation
  - Ensure minimized 1/rev flapping

Combined Sikorsky/NASA Conclusions/Recommendations

- SOF Monitoring (barchart)
  - Limits for Airloads SOF parameters still valid
  - Add new parameter (MRTEC5_0, max, min, hpp) to barchart to monitor blade TE compression
- Rotor Loads and Motion
  - Vibratory flapping limit needed to protect elastomeric bearing (current SOF limit is already lower than this)
  - Need to ensure flap stops not engaged at 40%RPM
    - Change lower flap stop springs to set engagement at 20-30% RPM
    - Remove upper flap stop spring and safety-wire flap stop in disengaged position
    - Verify correct engagement/disengagement (visual)
  - Running at positive shaft angles provide lowest loads
  - Could run out of control travel at some conditions
    - Cyclic required for min flapping highly dependent on collective and shaft angle
    - Approach conditions slowly to ensure adequate control travel

Combined Sikorsky/NASA Conclusions/Recommendations

- Ground Resonance and Stability
  - Damping coefficient for MR Damper (and subsequent NASA ground resonance analysis) suggests not testing near 80% nominal
    - Remove 80% RPM testing from plan
    - Monitor balance and lag motion for unusual behavior at reduced RPM
  - Damping margins for 1st flap and 1st torsion modes are reduced at lower RPMs
    - Monitor flap and torsion gage for unusual behavior

Combined Sikorsky/NASA Conclusions/Recommendations

- Operational Procedures
  - Test procedures should set RPM prior to raising tunnel speed to ensure don't dwell near 80% RPM
    - This is different from Sikorsky recommendation
  - Ensure SOP's, EOP's are understood and trained for/ practiced
  - On-line dynamics monitoring required per ground resonance/stability recommendations
    - Set up scope with 4 channels referenced to 1/rev
      - Lag damper motion, pitch link load, root flap bending, balance axial force gage (single post), oscillatory only
      - Look for amplitude or waveform changes at non-changing conditions
      - Look for non-harmonic behavior ("beating" of signals)

MG Set Failure Scenario

- NFAC (J. Barnes) performed early analysis of MG set failure and identified safety concerns that could preclude high mu testing
  - NFAC-provided rotor speed and tunnel velocity decay curves suggested that rotor RPM would drop below 75 RPM before tunnel velocity dropped to 15 kt
    - These values are/were the assumed limits for safe operation
  - Suggested that NASA may want to provide updated analysis to substantiate safe operation in this failure scenario

MG Set Failure Scenario

- NASA decided to address concerns in 5 steps
  - Step 1: Provide more realistic rotor speed and 40x80 velocity decay estimates
  - Step 2: Evaluate effects of starting RPM, starting torque/ power, and starting tunnel velocity on rotor speed and advance ratio
  - Step 3: Estimate minimum RPM and/or max advance ratio at which rotor is controllable as well as maximum tunnel speed where no rotor speed is required
  - Step 4: Perform CAMRAD predictions of proposed test envelope to determine expected control and rotor power requirements
  - Step 5: Based on information from steps 1-4, propose conditions at which we can safely test if an MG set failure occurs

Proposed SOP's

- Set Mtip (RPM) and nominal collective (4 deg)
- Set shaft angle
- Slowly increase tunnel speed to match mu
  - No more than 20 knot increments
  - Verify no time history anomalies, low loads
  - Adjust collective to keep power approximately constant (low power)
  - Minimize flapping at all times
- Data acquisition – collective sweep
  - Set collective to lowest value near zero power
  - Minimize flapping (no trim controller)
  - Acquire data
  - Perform collective sweep, acquiring data at even increments
    - Ensure total power is below max allowed for MG set failure at that speed
    - Return to nominal collective
  - Increase tunnel speed to match next mu and repeat data acquisition
- Return to low speed/hover to change RPM or alpha (until envelope cleared)

Proposed EOP's

- All EOP's identical to full RPM including RPM loss (i.e. MG set failure)
- If RPM loss
  - Ensure W.T. E-stop
  - Minimize flapping at all times
  - Set collective to 3 deg (nominal low power point)
- This approach
  - Minimizes rotor speed decay
  - Minimizes chance for rotor speed increase at high positive shaft angles

Slowed Rotor Test Description

Part of UH-60A Airloads Wind Tunnel Test Program (2010)

Norman, Shinoda, Peterson & Datta, AHS F , 2011

- **Slowed to 65% and 40% of Nominal RPM (NR)**
  - **- min RPM and max speed set by safety of flight**
  - **- sets max μ of 1.0**
- **Special motion & loads monitoring**
  - **- Sikorsky review**
- **Special operations**
  - **- RPM and shaft change always at zero speed**
- **Special procedure**
  - **- set RPM, shaft, speed and then sweep collective**
  - **- trim to minimize 1P flapping manually**

Summary and Conclusions

- First test of any production rotor at slowed RPM up to μ = 1.0

  - Fundamental characterization of dynamics
  - Exotic database for validation

- As μ increases, θ_{1S} increases, and together with high built-in twist drives advancing side outboard to local compressibility

- Reverse flow drives retreating side inboard center of pressure (c.p.) towards trailing-edge
  - observed new phenomena of reverse chord dynamic stall

Summary and Conclusions

- **3D unsteady pitching moments outboard (nose down) and reverse flow pitching moments inboard (nose up) produce high elastic twist**
  - **– creates high blade structural loads even with negligible total thrust**
  - **– creates dramatic negative lift (entire advancing side at μ=1.0)**

- **Vibratory hub loads benign due to vanishing 5/rev blade loads stemming from frequency gap between 2nd Flap (3.3/rev) and 1st Torsion (7.3/rev)**

- **Local compressibility and negative lift contribute to performance penalty**

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